Department I - C Plus Plus

Modern and Lucid C++ for Professional Programmers

Week 8 – STL Algorithms

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HS2023

OST

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Recap Week 7

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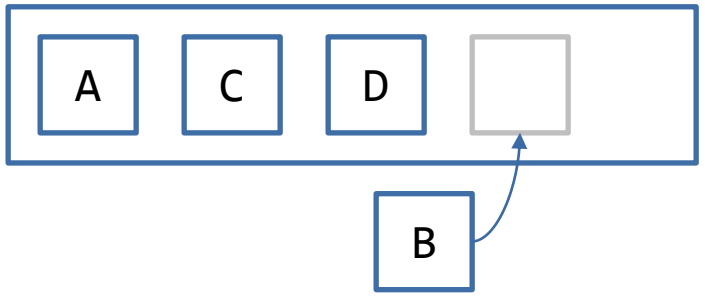
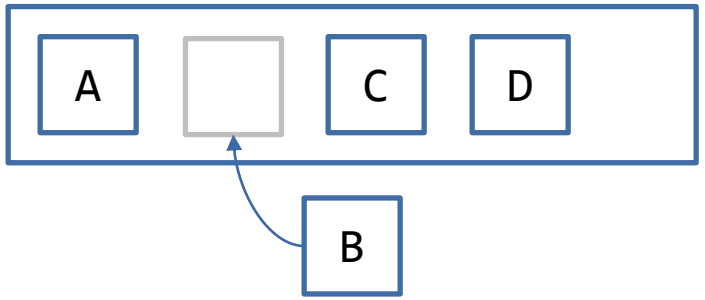
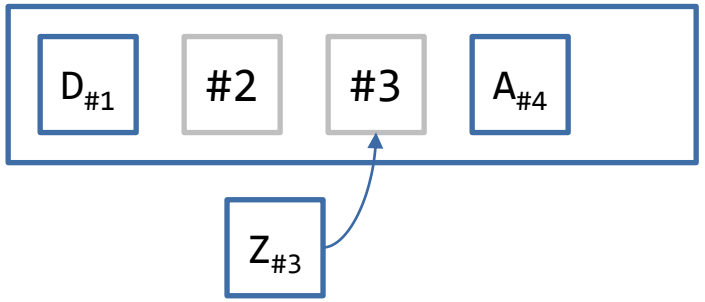
- **Sequence Containers**
  - Elements are accessible in order as they were inserted/created
  - Find in linear time through the algorithm find

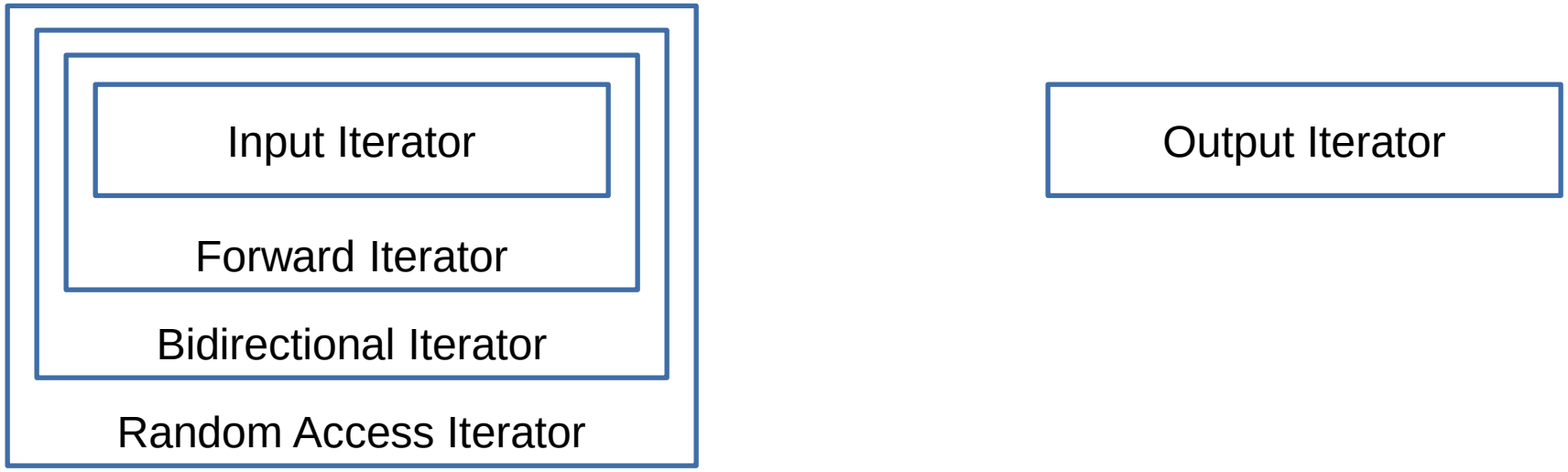


- **Associative Containers**
  - Elements are accessible in sorted order
  - `find` as member function in logarithmic time



- **Hashed Containers (Unordered Associative)**
  - Elements are accessible in unspecified order
  - `find` as member function in constant time

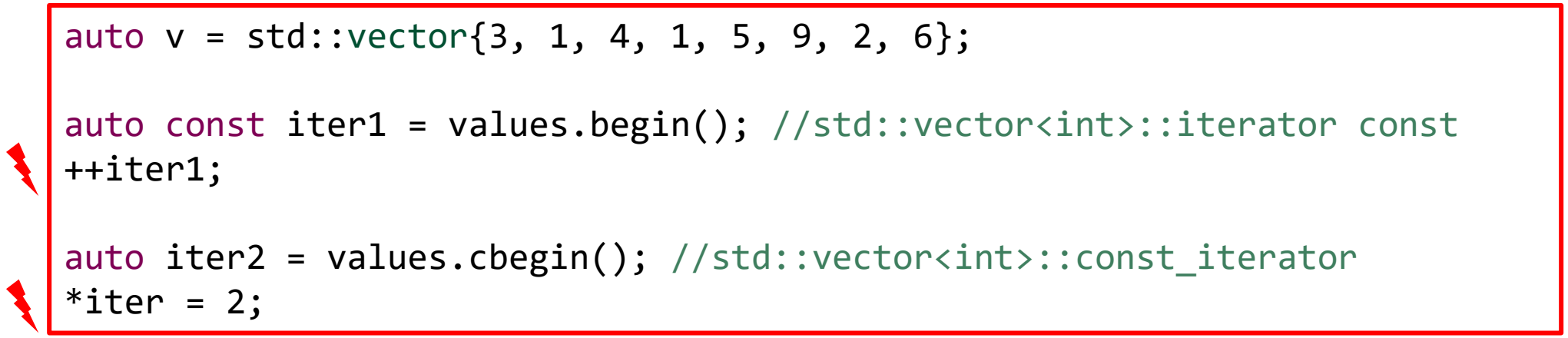




- **Different containers support iterators of different capabilities**
- **Categories are formed around increasing "power"**
  - `std::input_iterator` corresponds to istream_iterator's capabilities
  - `std::ostream_iterator` is an output_iterator
  - `std::vector<T>` provides random_access iterators

const_iterator != const Iterator

- **Declaring an iterator `const` would not allow modifying the iterator object**
  - You cannot call ++
- **`cbegin()` and `cend()` return const_iterators**
  - This does NOT imply the iterator to be `const`
  - The elements the iterator walks over are `const`



```
auto v = std::vector{3, 1, 4, 1, 5, 9, 2, 6};

auto const iter1 = values.begin(); //std::vector<int>::iterator const
++iter1;

auto iter2 = values.cbegin(); //std::vector<int>::const_iterator
*iter = 2;
```

- **`<algorithm>` header**
  - Filling
  - Finding
  - Property checking
  - Transformation
  - etc.
- **`<numeric>` header**
  - Generic numeric functions
  - Some functions can be applied in non-numeric contexts

- **Algorithms work with ranges specified by iterators**
- **Input**
  - 1 or 2 Ranges
  - Start
  - End (At least for first range)
- **Output**
  - Start
  - No end

Why should we use algorithms?

You know...

- ... why to prefer algorithms over loop
- ... the most important algorithms of the STL
- ... where the pitfalls are when using algorithms

You can...

- ... read and understand an algorithm signature/description
- ... use algorithms correctly

- **How do you reverse all elements of a vector?**

```
auto reverse(std::vector<int> & values) -> void {
  for (int i = 0; i <= values.size(); i++) {
    auto otherIndex{values.size() - i};
    auto tmp = values[0];
    values[i] = values[otherIndex];
    values[otherIndex] = values[i];
  }
}
```

- **How do you reverse all elements of a vector?**

```
auto reverse(std::vector<int> & values) -> void {
  for (int i = 0; i <= values.size(); i++) {
    auto otherIndex{values.size() - i};
    auto tmp = values[0];
    values[i] = values[otherIndex];
    values[otherIndex] = values[i];
  }
}
```

- **Algorithms are less error-prone**

```
auto reverse(std::vector<int> & values) -> void {
  reverse(begin(values), end(values));
}
```

- **What does the code do?**

```
auto ???????(std::vector<int> values) -> int {
  auto var = std::numeric_limits<int>::min();
  for (auto v : values) {
    if (v > var)
      var = v;
  }
  return var;
}
```

- **Algorithms can be much clearer regarding the programmer's intention**

```
auto ???????(std::vector<int> values) -> int {
  if (values.empty()) {
    return std::numeric_limits<int>::min();
  }
  return *std::max_element(begin(values), end(values));
}
```

- **How many times is the condition evaluated?**

```
auto contains(std::vector<int> values, int sought) -> bool {
  for (auto it = begin(values); it != end(values); it++) {
    if (*it == sought) return true;
  }
  return false;
}
```

- **And now?**

```
auto contains(std::vector<int> values, int sought) -> bool {
  return find(begin(values), end(values), sought) != end(values);
}
```

- **To be fair: A modern compiler will optimize the condition in the `for` loop**
  - Nevertheless, an algorithm can be implemented to be more efficient than a hand-written loop

Why Should we use Algorithms?

- **Correctness**
  - It is much easier to use an algorithm correctly than implementing loops correctly
- **Readability**
  - Applying the correct algorithm expresses your intention much better than a loop
  - Someone else (or even you) will appreciate it when the code is readable and easily understandable
- **Performance**
  - Algorithms might perform better than handwritten loops
    - without sacrificing the "Readability" of your code

Algorithm Basics

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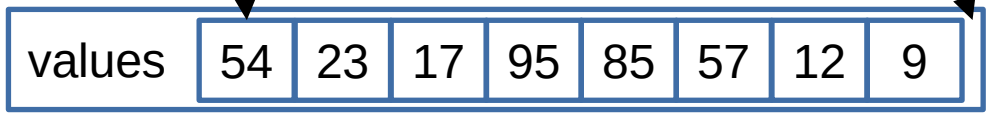
- **Iterators specify ranges used for algorithms**
  - `First` – Iterator pointing to the first element in the range
  - `Last` – Iterator pointing beyond the last element in the range
  - If `First == Last` the range is empty

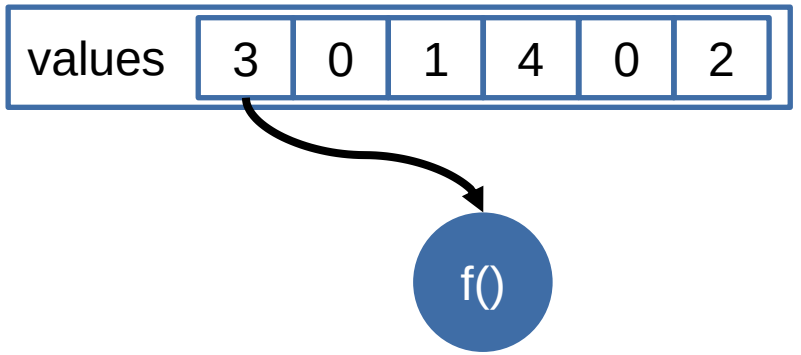
```
std::vector<int> values{54, 23, 17, 95, 85, 57, 12, 9};
std::xxx(begin(values), end(values), ...);
```



- **Streams need a wrapper to be used with algorithms**
  - `std::ostream -> std::ostream_iterator<T>`
  - `std::istream -> std::istream_iterator<T>`
  - Default-constructed `std::istream_iterator<T>` marks EOF

```
auto redirect(std::istream & in, std::ostream & out) -> void {
  using in_iter = std::istream_iterator<char>;
  using out_iter = std::ostream_iterator<char>;
  std::copy(in_iter{in}, in_iter{}, out_iter{out});
}
```

- **Executing an operation for each element in a range**
- **Operation is a function, lambda or functor**
  - Which is called for each element
- **Input iterators for range**
- **Returns the function/object passed as operation**




```
auto values = std::vector{3, 0, 1, 4, 0, 2};

auto f = [](auto v) {};
std::for_each(begin(values), end(values), f);
```

Reading Algorithm Signatures

- **Signature of `std::for_each` from cppreference.com:**

Template Header		
`template<class InputIt, class UnaryFunction>`		
`UnaryFunction`	**`for_each`**`(InputIt first, InputIt last, UnaryFunction f);`	
Returntype	*Name*	*Parameters*

- **Each algorithm has**
  - A name
  - Parameters
  - A return type or is `void`
- **The description specifies the requirements**
- **Parameter and return types are usually template parameters (next week)**

- **Algorithms work with the iterator categories**
  - Input iterator
  - Forward iterator
  - Bidirectional iterator
  - Random access iterator
  - Output iterator

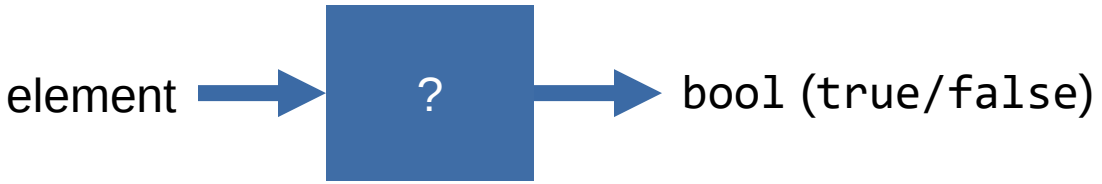
- **A functor is a type (class) that provides a call operator: `operator()`**
  - An object/instance of that type can be called like a function
  - It can provide multiple overloads of the call operator (usually not necessary)
  - Can take any number of parameters and have an arbitrary return type
- **Lambdas are realized with functors internally**

```
struct Accumulator {
  int count{0};
  int accumulatedValue{0};
  auto operator()(int value) -> void {
    count++;
    accumulatedValue += value;
  }
  int average() const;
  int sum() const;
};

auto average(std::vector<int> values) -> int {
  Accumulator acc{};
  for(auto v : values) { acc(v); }
  return acc.average();
}
```

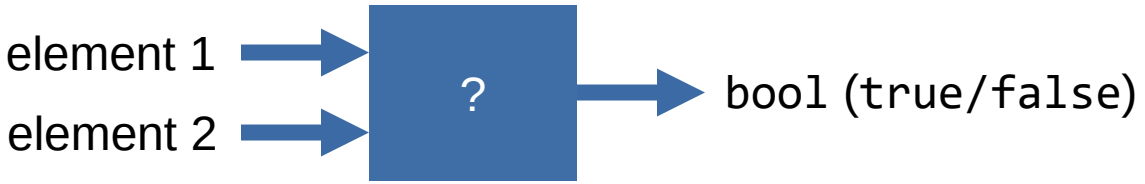
```
auto average(std::vector<int> values) -> int {
  auto acc = Accumulator{};
  return std::for_each(begin(values), end(values), acc).average();
}
```

- **Predicate: A function or a lambda returning bool (or a type convertible to bool)**
  - For checking a criterion/condition
- **Unary Predicate**
  - One parameter




```
auto is_odd = [](auto i) -> bool {return i % 2;};
```

- **Binary Predicate**
  - Two parameters




```
auto divides = [](auto i, auto j) -> bool {return !(i % j);};
```

`#include <functional>`

- **Lambdas make applying transform etc. quite easy**

```
transform(v.begin(), v.end(), v.begin(), [](auto x){return -x;});
```

- **However, if there is only a simple expression used, there is a chance for reuse**
  - of the standard library's functor classes for almost all operators

```
transform(v.begin(), v.end(), v.begin(), std::negate<>{});
```

  - also relational operators, e.g., sorting in descending order

```
sort(v.begin(), v.end(), std::greater<>{});
```

#include <functional>

- **Binary arithmetic and logical**
  - plus<> (+)
  - minus<> (-)
  - divides<> (/)
  - multiplies<> (*)
  - modulus<> (%)
  - logical_and<> (&&)
  - logical_or<> (||)
- **unary**
  - negate<> (-)
  - logical_not<> (!)
- **binary comparison**
  - less<> (<)
  - less_equal<> (<=)
  - equal_to<> (==)
  - greater_equal<> (>=)
  - greater<> (>)
  - not_equal_to<> (!=)

```
transform(v.begin(), v.end(), v.begin(), v.begin(), std::multiplies<>{});
```

- **Associative containers allow an additional template argument for the comparison operation**
  - It must be a functor class giving a binary predicate
  - Predicate must be irreflexive and transitive

```
std::set<int, std::greater<>> reverse_int_set{};
```

- **Own functors can provide special sort order, e.g., case-less comparison of strings**
  - Caution: requirements for sorting must be fulfilled,
    - e.g. `>= (std::greater_equal)` is not allowed (is reflexive!)

Example: set<string> for dictionary


```
#include <set>
#include <algorithm>
#include <cctype>
#include <iterator>
#include <iostream>
struct caseless {
  using string = std::string;
  auto operator()(string const & l, string const & r) const -> bool {
    return std::lexicographical_compare(
                    l.begin(), l.end(), r.begin(), r.end(),
                    [](char l, char r){
                      return std::tolower(l) < std::tolower(r);
    });
  }
};
auto main() -> int {
  using std::string;
  using caseless_set = std::multiset<string, caseless>;
  using in = std::istream_iterator<string>;
  auto const wlist = caseless_set{in{std::cin},in{}};
  auto out = std::ostream_iterator<string>{std::cout,"\n"};
  copy(wlist.begin(), wlist.end(), out);
}
```

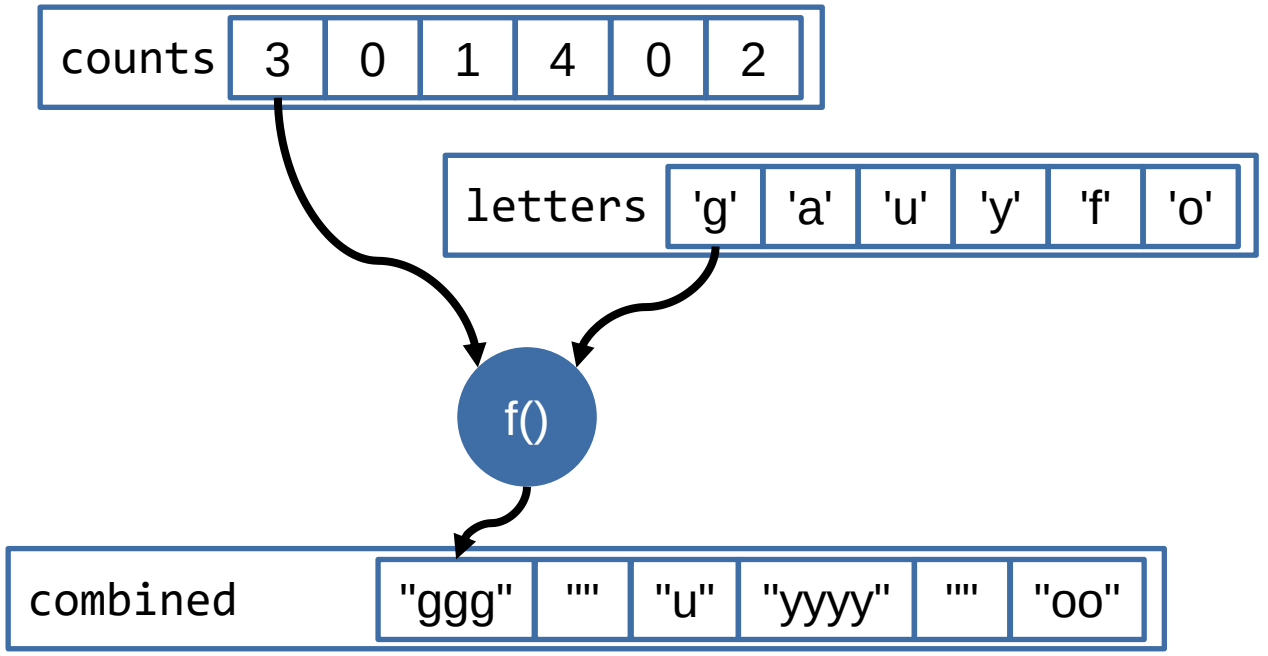
Binary Predicate

Strings as Ranges

Lambda as Binary Predicate on char

Pass Predicate Functor as Template Argument

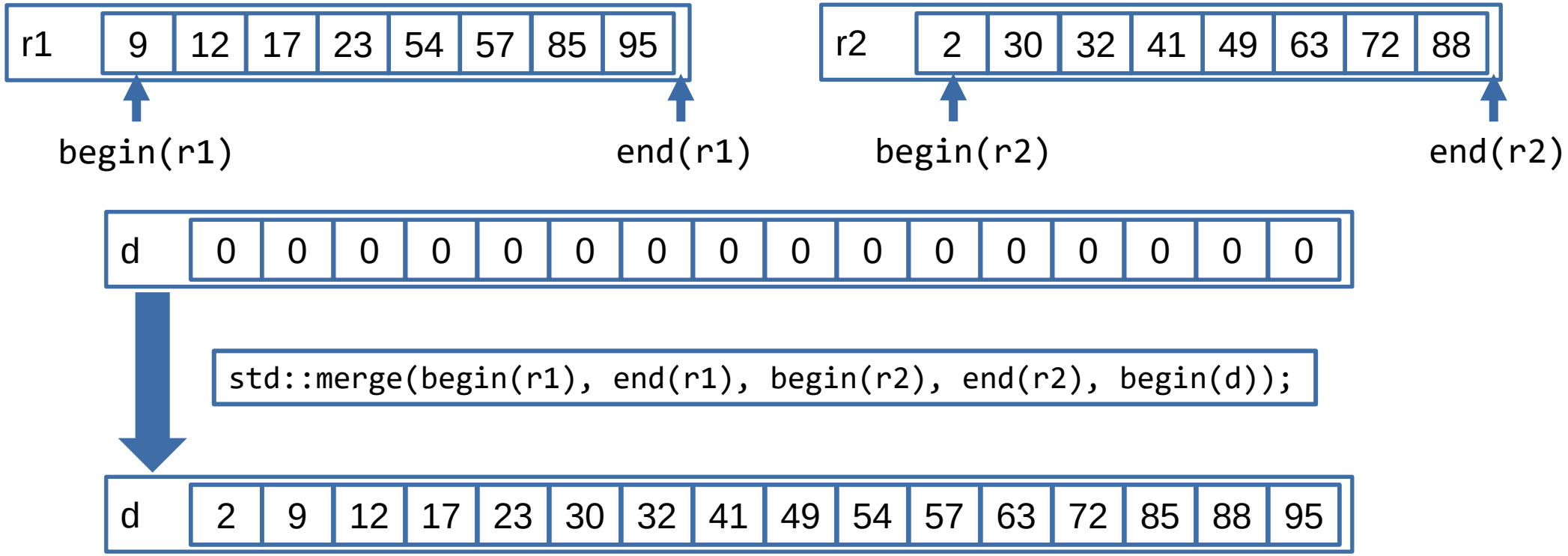
- **Mapping one range to new values**
  - Or two ranges of same size
- **Lambda/function/functor for map operation**
- **Input and output types can be different**
  - As long as the operation has the correct types




```
auto counts = std::vector{3, 0, 1, 4, 0, 2};
auto letters = std::vector{'g', 'a', 'u', 'y', 'f', 'o'};
auto combined = std::vector<std::string>{};
auto times = [](auto i, auto c) { return std::string(i, c); };
std::transform(begin(counts), end(counts), begin(letters),
               std::back_inserter(combined), times);
```

- **Merging two SORTED (!) ranges**

```
std::vector r1{9, 12, 17, 23, 54, 57, 85, 95};
std::vector r2{2, 30, 32, 41, 49, 63, 72, 88};
std::vector d(r1.size() + r2.size(), 0);
```



Right or Wrong?

?

```
std::ostream_iterator<int> out{std::cout, ","};
int main() {
  std::set odd{1, 5, 7, 3, 9};
  std::set even{2, 8, 6, 4, 10};
  std::vector<int> all{};
  merge(begin(odd), end(odd),
        begin(even), end(even),
        std::back_inserter(all));
  copy(begin(all), end(all), out);
}
```

Correct

`merge` requires sorted ranges. The ranges in a set are sorted.

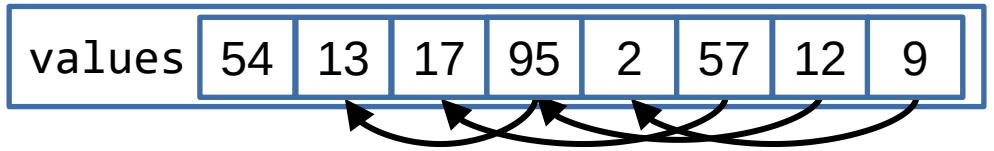
```
int const minusIndex = 10;

auto splitDigits(int number) {
  std::string digits = std::to_string(number);
  std::vector<unsigned> indices(digits.size());
  transform(begin(digits), end(digits),
            begin(indices),
            [](char c) {
    return c == '-' ? minusIndex : c - '0';
  });
  return indices;
}
```

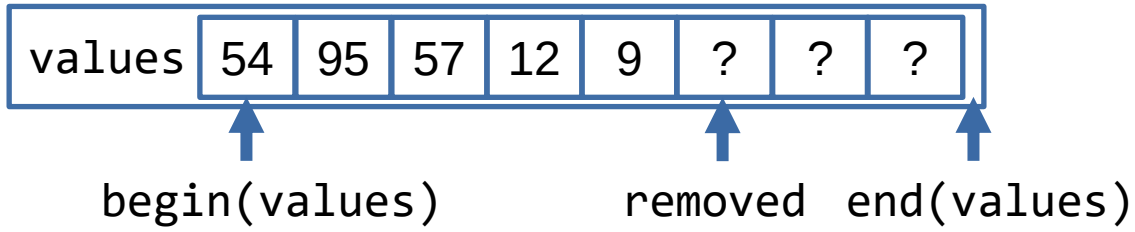
Correct

As long as the vector `indices` has enough elements, which can be overwritten, this code is correct.

- **`std::remove` does NOT actually remove the elements**
  - It moves the "not-removed" elements to the front and returns an iterator to the end of the "new" range

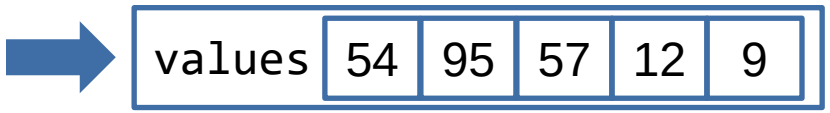



```
auto values = std::vector{54, 13, 17, 95, 2, 57, 12, 9};
auto is_prime = [](unsigned u) {/*...*/};
auto removed = std::remove_if(begin(values), end(values), is_prime);
```

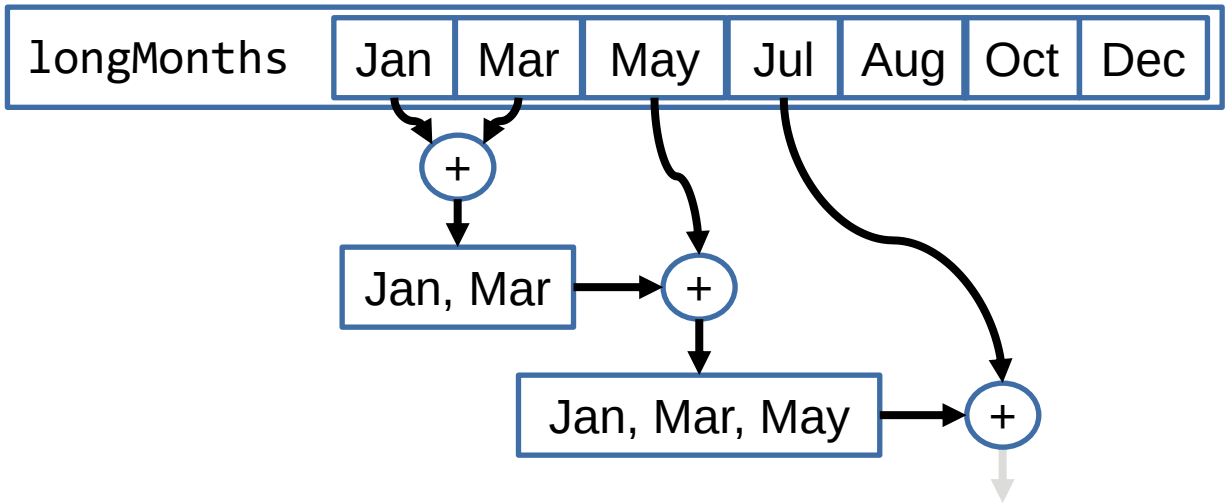


- **To get rid of the "removed" elements usually the "erase" member function is called**

```
values.erase(removed, values.end());
```



- **Some numeric algorithms can be used in non-numeric contexts**
- **Example `std::accumulate`**
  - Sums elements that are addable (+ operator)
  - Or based on a custom binary function
  - Returns the "sum" (accumulated value)




```
std::vector<std::string> longMonths{"Jan", "Mar", "May", "Jul", "Aug", "Oct", "Dec"};
auto accumulatedString = std::accumulate(
        next(begin(longMonths)), //Second element
        end(longMonths),         //End
        longMonths.at(0),        //First element, usually the neutral element
        [](std::string const & acc, std::string const & element) {
                return acc + ", " + element;
        }); //Jan, Mar, May, Jul, Aug, Oct, Dec
```

- **Some algorithms have a variation with the _if suffix**
  - They take a predicate (instead of a value) to provide a condition

```
auto numbers = std::set{1, 2, 3, 4, 5, 6, 7, 8, 9};
auto isPrime = [](auto u) {/*...*/};
auto nOfPrimes = std::count_if(begin(numbers), end(numbers), isPrime);
```

- **Algorithms with the _if suffix**
  - count_if
  - copy_if
  - replace_if
  - find_if
  - remove_if
  - replace_copy_if
  - find_if_not
  - remove_copy_if

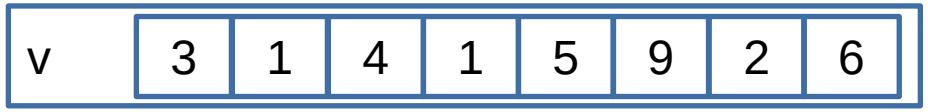
- **Some algorithms have a variation with the _n suffix**
  - The _n suffix is related to a number provided (usually instead of the "last" iterator)

```
auto numbers = std::set{1, 2, 3, 4, 5, 6, 7, 8, 9};
auto top5 = std::vector<int>(5);
std::copy_n(rbegin(numbers), 5, begin(top5));
```

- **Algorithms with the _n suffix**
  - `search_n`
  - `fill_n`
  - `for_each_n`
  - `copy_n`
  - `generate_n`

- **Implementing a binary heap on a sequenced container**
- **Requires random access iterator**
- **Guarantees:**
  - Top element is the largest (max)
  - Adding and removing elements have performance guarantees
- **Used for implementing priority queues**
- **Heap operations**
  - `make_heap` (3 * N comparisons)
  - `pop_heap` (2 * log(N) comparisons)
  - `push_heap` (log(N) comparisons)
  - `sort_heap` (N*log(N) comparisons)

Heap Example



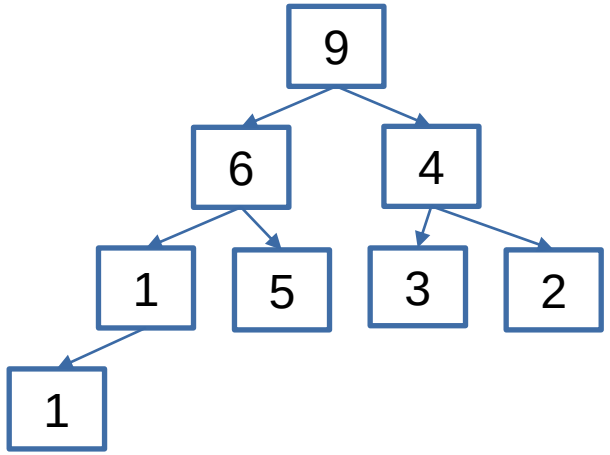

```
std::vector<int> v{3,1,4,1,5,9,2,6};
make_heap(v.begin(),v.end());
pop_heap(v.begin(),v.end());
v.pop_back();
v.push_back(8);
push_heap(v.begin(),v.end());
sort_heap(v.begin(),v.end());
```

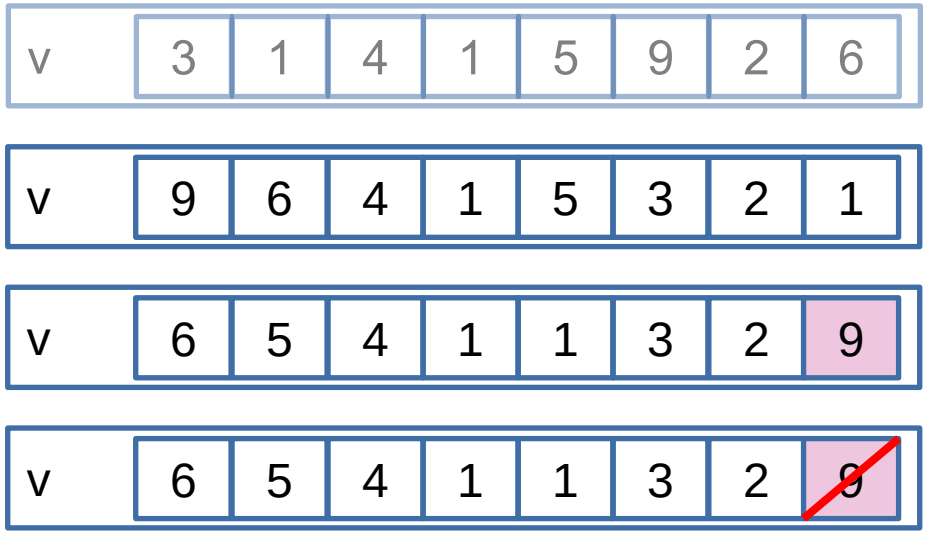
Heap Example: `make_heap`

v	3	1	4	1	5	9	2	6

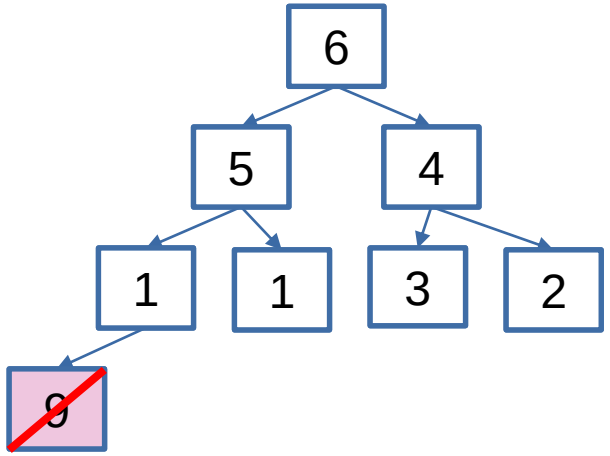
v	9	6	4	1	5	3	2	1

```
std::vector<int> v{3,1,4,1,5,9,2,6};
make_heap(v.begin(),v.end());
pop_heap(v.begin(),v.end());
v.pop_back();
v.push_back(8);
push_heap(v.begin(),v.end());
sort_heap(v.begin(),v.end());
```

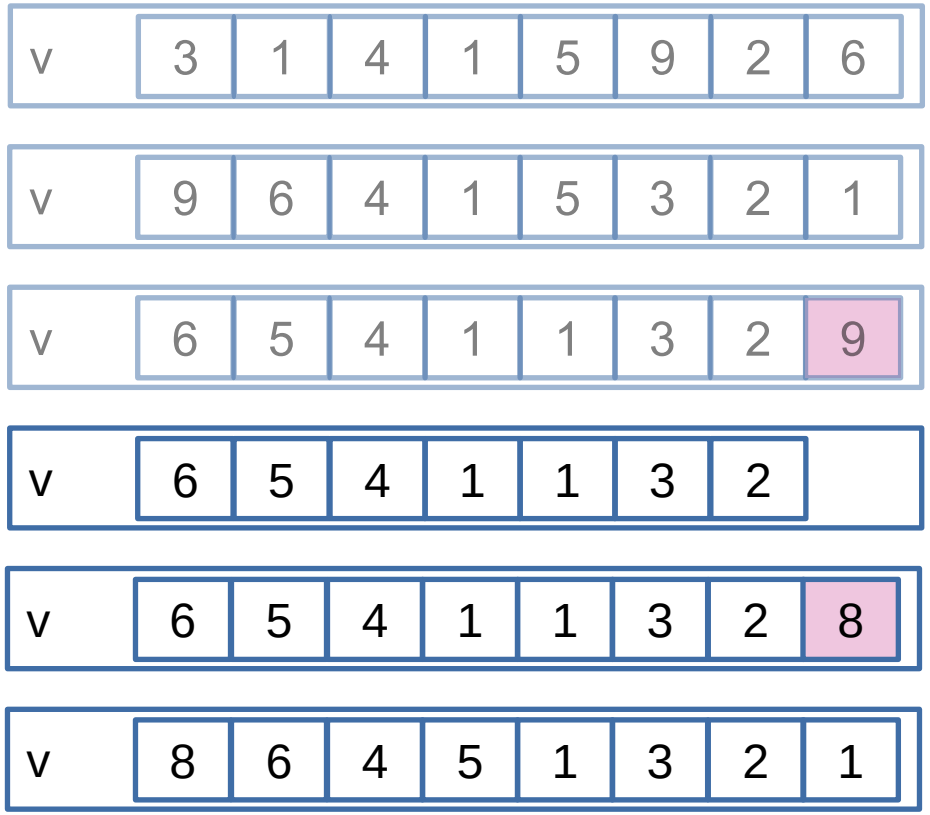




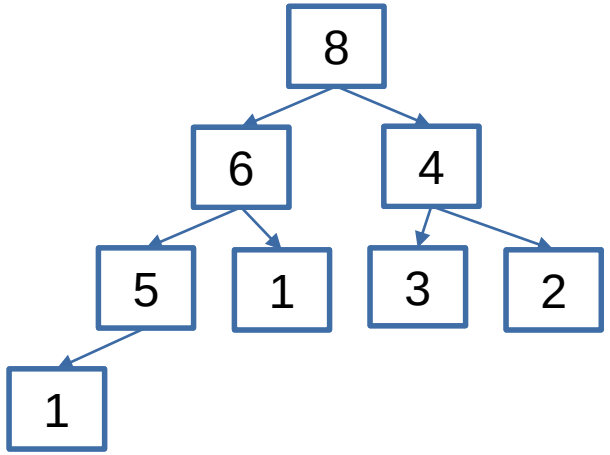

```
std::vector<int> v{3,1,4,1,5,9,2,6};
make_heap(v.begin(),v.end());
pop_heap(v.begin(),v.end());
v.pop_back();
v.push_back(8);
push_heap(v.begin(),v.end());
sort_heap(v.begin(),v.end());
```



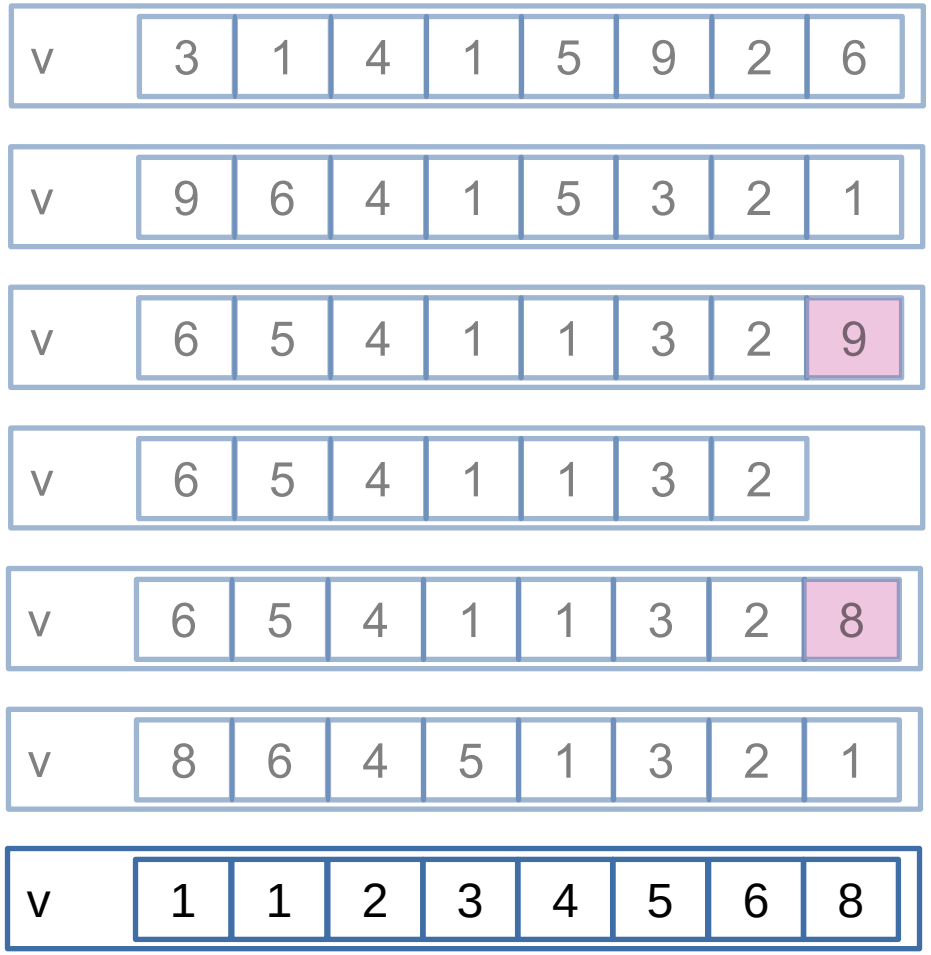
Heap Example: push_heap




```
std::vector<int> v{3,1,4,1,5,9,2,6};
make_heap(v.begin(),v.end());
pop_heap(v.begin(),v.end());
v.pop_back();
v.push_back(8);
push_heap(v.begin(),v.end());
sort_heap(v.begin(),v.end());
```



Heap Example: `sort_heap`




```
std::vector<int> v{3,1,4,1,5,9,2,6};
make_heap(v.begin(),v.end());
pop_heap(v.begin(),v.end());
v.pop_back();
v.push_back(8);
push_heap(v.begin(),v.end());
sort_heap(v.begin(),v.end());
```

Pitfalls

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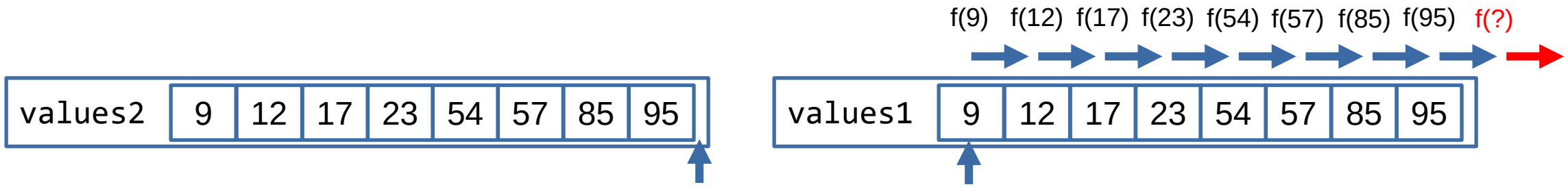
- **It is mandatory that the iterators specifying a range need to belong to the same range**
- **Advancing the "first" iterator has to reach the "last" iterator eventually (without leaving the range)**
- **Otherwise, access of the value might result in undefined behavior**



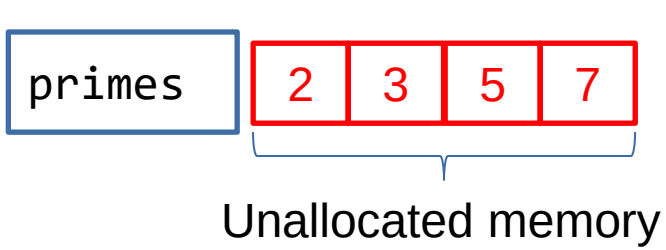

```
std::vector<unsigned> values1 = create_vector();
std::vector<unsigned> values2 = create_vector();

auto f = [](unsigned u) {/*...*/};
std::for_each(begin(values1), end(values2), f);
```

- **If you use an iterator for specifying the output of an algorithm you, need to make sure that enough space is allocated**

```
std::set<unsigned> numbers{1, 2, 3, 4, 5, 6, 7, 8, 9};
std::vector<unsigned> primes{};
auto isPrime = [](unsigned u) {/*...*/};
std::copy_if(begin(numbers), end(numbers), begin(primes), isPrime);
```

- **Vector `primes` is empty, which will not be changed by the iterator passed to `copy`**

- **The output is copied into (possibly) unallocated memory**

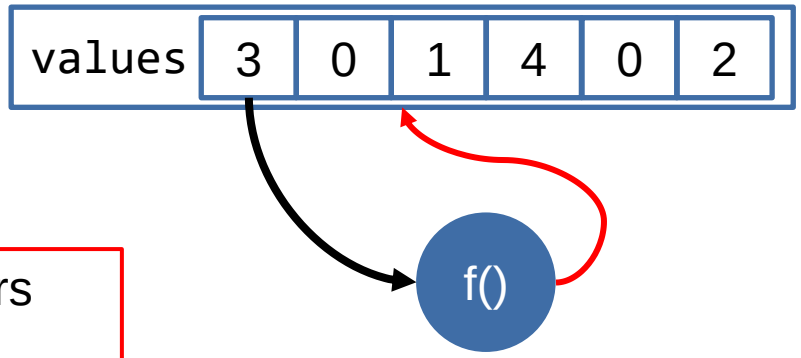


- **What if we want to insert elements into a container without pre-allocating the required memory?**
- **There are three inserter functions for wrapping containers that take care of this case**
  - `back_inserter`
    - Creates an `std::back_insert_iterator`, which uses the `push_back` member function of the container
  - `front_inserter`
    - Creates an `std::front_insert_iterator`, which uses the `push_front` member function of the container
  - `inserter`
    - Creates an `std::insert_iterator`, which uses the insert member function of the container

```
std::set<unsigned> numbers{1, 2, 3, 4, 5, 6, 7, 8, 9};
std::vector<unsigned> primes{};
auto is_prime = [](unsigned u) {/*...*/};
std::copy_if(begin(numbers), end(numbers), back_inserter(primes), is_prime);
```

Pitfall: Input Invalidation

- **Some operations on containers invalidate its iterators**
- **Example:**
  - `std::vector<T>::push_back`



If the new size() is greater than capacity() then all iterators and references (including the past-the-end iterator) are invalidated. Otherwise only the past-the-end iterator is invalidated. [1]

```
std::vector<unsigned> values{3, 0, 1, 4, 0, 2};

auto f = [&values](unsigned v) {
  values.push_back(v);
};

std::for_each(begin(values), end(values), f);
```

[1] http://en.cppreference.com/w/cpp/container/vector/push_back


```
bool isPrime(int value);

auto primes(std::vector<unsigned> const & values) {
  std::vector<unsigned> primeValues{};
  copy_if(begin(values), end(values),
          back_inserter(primeValues),
          isPrime);
  return primeValues;
}

int main() {
  std::istream_iterator<unsigned> inIter{std::cin};
  std::istream_iterator<unsigned> eof{};
  std::vector<unsigned> const values{inIter, eof};
  std::ostream_iterator<unsigned> out{std::cout};
  copy(begin(primes(values)), end(primes(values)), out);
}
```

Incorrect

Because primes returns a vector by value, the range in main is specified over two different instances of `vector`. The resulting behavior is undefined. Possibly, nothing is printed at all or the `copy` algorithm might continue copying the memory to the output as it never reaches end.

- **C++20 introduces a “codified” concept of ranges**
  - A range has a beginning and end.
    - `std::ranges::begin, std::ranges::end`
  - Algorithms defined in <algorithm> have ranges equivalents:
    - `std::ranges::for_each`
    - `std::ranges::count_if`
    - `std::ranges::transform`
    - …
  - Prevents some misuses and cleans up the API

- Given a vector

```
auto values = std::vector<int>{3, 1, 4, 1, 5, 9}
```

- Reversing the vector using “classic” algorithms:

```
std::reverse(begin(values), end(values));
```

- Reversing the vector using `std::ranges`

```
std::ranges::reverse(values);
```

Algorithm Headers

OST
Ostschweizer
Fachhochschule

- **Algorithms header**
  - Non-modifying sequence operations
  - Mutating sequence operations
  - Sorting and related operations
  - C library algorithms
- **Numerics header**
  - `accumulate`
  - `inner_product`
  - `partial_sum`
  - `adjacent_difference`
  - `iota`

Algorithms: Non-Modifying Sequence Operations

- `all_of`
- `any_of`
- `none_of`

condition checking

- `for_each`
- `mismatch`
- `equal`

comparing ranges

- `is_permutation`
- `find, find_if, find_if_not`
- `find_end`
- `find_first_of`
- `adjacent_find`
- `count, count_if`
- `search, search_n`

finding elements

- `copy, copy_n, copy_if, copy_backward`
- `move, move_backward`
- `swap_ranges`
- `transform`
- `replace, replace_if, replace_copy, replace_copy_if`
- `fill, fill_n`
- `generate, generate_n`
- `remove, remove_if, remove_copy, remove_copy_if`
- `unique, unique_copy`
- `reverse, reverse_copy`
- `rotate, rotate_copy`
- `shuffle`
- `is_partitioned, partition, stable_partition, partition_copy, partition_point`

- `sort, stable_sort, partial_sort, partial_sort_copy`
- `is_sorted`
- `nth_element`
- `lower_bound, upper_bound, equal_range`
- `binary_search`
- `merge, inplace_merge`
- `includes, set_union, set_intersection, set_difference, set_symmetric_difference`
- `push_heap, pop_heap, make_heap, sort_heap`
- `is_heap_until, is_heap`
- `min, max, minmax`
- `min_element, max_element, minmax_element`
- `next_permutation, prev_permutation`

- **Additional algorithms might come in the future**
- **Some algorithms can be parameterized by execution policies**
  - New first parameter of type ExecutionPolicy
  - `std::execution::sequenced_policy` (`std::execution::seq`)
    - Executed in the calling thread
  - `std::execution::parallel_policy` (`std::execution::par`)
    - May be executed in another thread
  - `std::execution::parallel_unsequenced_policy` (`std::execution::par_unseq`)
    - May be executed in other threads and vectorized

- **Use algorithms whenever they are more expressive and shorter to use than loops**
- **Function, lambdas and functors can be passed as arguments of the algorithm's actions and predicates**
- **Don't invalidate your iterators as a side-effect**
- **Ensure you get your memory management right for an algorithm's output**
- **Familiarize yourself with the available algorithms**

```
#include <boost/iterator/counting_iterator.hpp>
#include <boost/iterator/filter_iterator.hpp>
#include <boost/iterator/transform_iterator.hpp>
```

- **Several pre-defined adapters with factory functions, for example**
  - Counting
  - Filtering
  - Transforming